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LIGHT FRAGMENT EMISSION AND MULTIFRAGMENTATION ?

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Résumé - Les fragments légers observés aux énergies intermédiaires constituent une nouvelle classe de produits de réaction dans les collisions d'ions lourds. Si deux modes de production semblent bien compris, un troisième identifié à l'aide d'une paramétrisation en terme de source reste plus difficile à définir. Quelques caractéristiques de ce dernier mode sont présentées à partir de données inclusives et d'éventuelles signatures d'un processus de multifragmentation sont discutées.

Abstract - Light fragments have been observed as a new class of products from heavy-ion collisions at intermediate energies. Two mechanisms which produce such light fragments are well understood but is seems difficult to characterize a third one identified within a moving source framework. From a large set of inclusive data, a few features are extracted and eventual signatures of a multifragmentation process are discussed.

I - INTRODUCTION

The emission of light fragments ($4 \leqslant Z \leqslant 15$), also called intermediate mass fragments, was first observed in high and intermediate energy hadron-nucleus collisions /1,2/ and has been associated with the most violent of these reactions. Light fragments have also been observed in nucleus-nucleus collisions at high incident energies /3,4/ and more recently, with the development of new facilities as GANIL, NSCL and SARA, investigations on such reaction products in the intermediate energy range have been performed /5,6,7/.

Numerous mechanisms have been proposed to explain this light fragment production including the direct cleavage of the target nucleus by the incident projectile /8,9/, sequential statistical emission from localized hot zones /10,11/, statistical multifragmentation /12,13,14,15/, nuclear fragmentation within percolation models /16,17/, dynamical multifragmentation /18/, the coalescence model (3,19/, the random shattering of a cold nucleus by the projectile /20/ and the statistical formation of clusters near the critical point in the liquid-gas phase diagram of nuclear matter /21,22,23/. However, light fragment emission has also been observed in the decay of fusion nucleus at relatively low incident energies /24/ and this decay mode of statistically equilibrated nuclei /25/ is expected to increase with excitation energy. As a consequence the experimental situation concerning light fragment production in nucleus-nucleus collisions at intermediate energies, where fusion-like processes subsist, appears to be more complicated than at higher or lower incident energies.

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In this paper, I shall restrict the discussion to the study of light fragment produced in central collisions which could be connected with the first set of mentioned models /8-23/. For this purpose I have selected experiments for which the fusion-like component could be subtracted or was negligible. From a large set of data I shall try to extract a few features which can be used as a guide for exclusive measurements. One of the fundamental question in studying heavy-ion reactions at intermediate energies is how the highly excited nuclear system formed in central collisions disassembles. Multifragmentation processes have been discussed in many theoretical works and I shall try to discuss eventuel experimental signatures of such mechanisms.

I shall use along the paper some abreviations that I mention now: light fragment (LF), projectile-like-fragment (PLF), deep inelastic collisions (DIC), intermediate velocity source (IVS), fusion-like component (FLC).

II - LIGHT FRAGMENT EMISSION: MOVING SOURCE ANALYSIS

Before discussing heavy-ion collisions, let me start with results obtained using an ^{3}He beam. Relative to heavy-ions one has the advantage of unambiguous identification of LF at very forward angles. LF have been measured by Kwiatkowski et al. /26/ bombarding a silver target at 200 MeV incident energy. Figure 1 shows a plot in the velocity plane of the invariant cross-section for carbon fragments which is typical of the results for all LF products. By means of such a diagram one can easily determine whether or not a rest frame exists from which the emission appears isotropic. At large angles ($\gtrsim 90°$) invariant cross sections fall on circles centered at an average velocity nearly equal to that of the compound nucleus which gives evidence for isotropic emission. In contrast, the forward angle data have tails

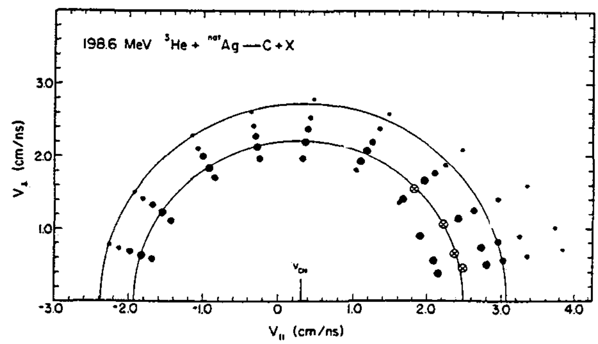

Fig. 1 - Plot of the invariant cross-section for carbon fragments in the velocity plane. The diameter of the dots is proportional to the cross-sections. The symbol ⊗ indicates the position of the maxima at forward angles. V_{CN} is the compound nucleus velocity. From /26/.

extending to much larger velocities, indicating emission from a faster moving source. In figure 2, contour plots of invariant cross-sections are presented for different elements produced in reactions induced by a 27 MeV/u argon beam /6/. Here we have an overview of the situation at forward angles when heavy projectiles are involved and it seems much more complicated. Clearly appears a high velocity component as circles centered at a velocity slightly lower than the beam velocity, which corresponds to the production of PLF in peripheral collisions /27,28/. What is more surprising is the shape of the contours in the lower parallel velocity part. As a first possible explanation we have to consider a dominant process of the low energy regime which can give

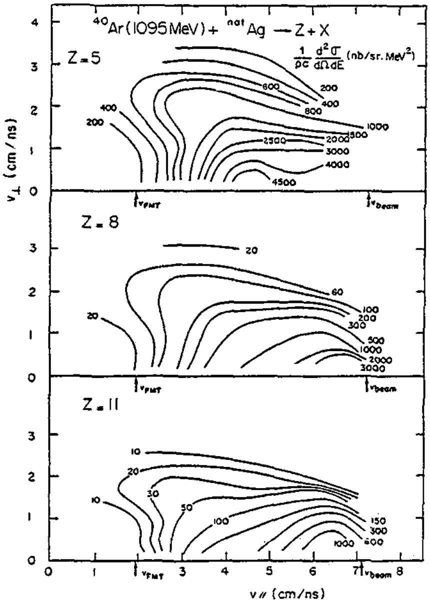

Fig. 2 - Contour plots of invariant cross-sections for different elements as a function of parallel and transverse velocities. V_{FMT} is the compound nucleus velocity. From /6/.

birth to this relaxed component: DIC. However fragment-fragment correlation studies performed for this system at 35 MeV/u /29/ indicate the quasi inexistence of binary events (σ_{binary} < 1 mb) and the same conclusion was derived from the Kr + Au study at 35 MeV/u /30/. Consequently it appears that at these relative velocities, the interaction time becomes too short to allow a composite system to be formed between the two interacting nuclei and we have to call for other processes to explain the observed component. On the basis of the angular distributions, kinetic energy spectra and contour plots of invariant cross-sections, many authors have adopted a two or three source parametrization (depending on the angular detection range) for the interpretation of the data. One source is relative to the production of PLF, with velocity close to the beam velocity, the second assumes statistical emission of LF from an equilibrated fusion-like nucleus whereas the third one is approximated by an IVS. Then the data can be fitted in the most complete and general form by:

$$\left(\frac{d^2\sigma}{d\Omega dE}\right)_Z = \sigma_{PLF}\, f_1(v_1, \sigma_\parallel^2, \sigma_\perp^2) + \sigma_{FLC} f_2\, (v_2, T_2, p_Z, C_2) + \sigma_{IVS} f_3\, (v_3, T_3, C_3)$$

where v_i is the source velocity, $\sigma_\parallel^2$ and $\sigma_\perp^2$ are respectively longitudinal and transverse variances of momenta /28/, T_i is a temperature parameter, p_Z is a Z-dependent amplification parameter /25/ and C_i the fractional Coulomb barrier. The total cross-sections for the different components and for a fragment Z are given by σ_{PLF}, σ_{FLC} and σ_{IVS} respectively. The functions f_1, f_2 and f_3 contain appropriate kinetic transformations from the moving frame to the laboratory system.

Examples of such parametrizations are presented in figure 3. With heavy-ion projectiles the energy spectra measured at laboratory angles larger than 30° are well reproduced using only two sources (FLC and IVS). We can also emphasize, in the case of the ^{3}He beam, the good agreement between the data and the fit even at very forward angle ; this last result gives more confidence in the parametrization of the

IVS. What mechanism hides behind the IVS is the question we can try to answer.

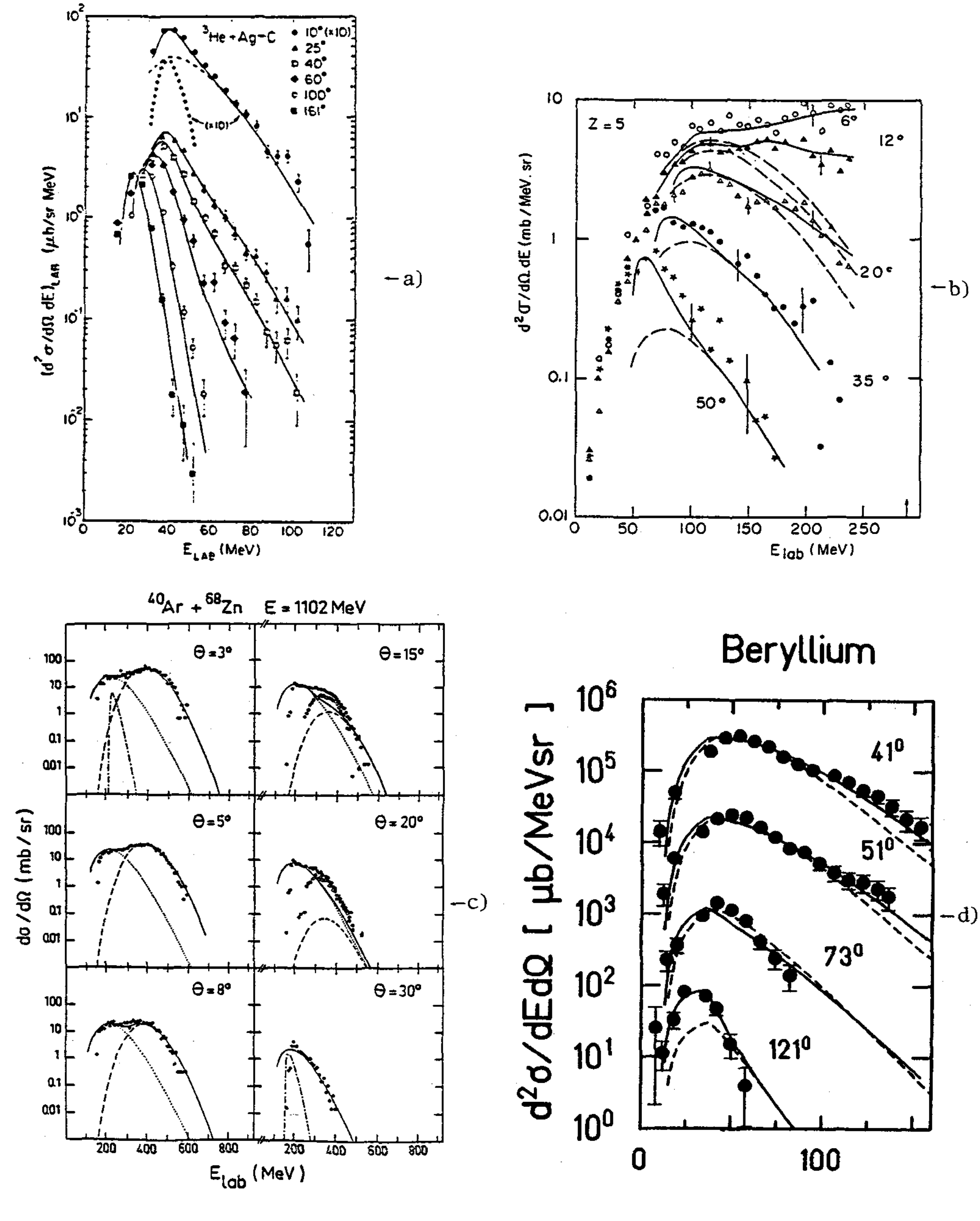

Fig. 3 - Examples of LF energy spectra as a function of angle. (a) 200 MeV ^{3}He+Ag → C; (b) 1095 MeV Ar+Ag → B; (c) 1102 MeV Ar+Zn → O; (d) 1512 MeV ^{18}O+Au → Be. Solid lines denote the spectra calculated using two or three sources. The IVS corresponds to dashed lines for (a), (b), (d) and to dotted lines for (c). From /6,26,31,32/.

III - THE INTERMEDIATE VELOCITY SOURCE

The general form for the differential cross-section at a detection angle Θ and for a given Z is:

$$\left(\frac{d^2\sigma}{d\Omega dE}\right)_{lab} \propto (E - ZC_3)^{\alpha} \exp-[(E - ZC_3 + E_3 - 2 E_3^{\frac{1}{2}}(E - ZC_3)^{\frac{1}{2}} \cos\Theta)/T_3]$$

where E_3 is the energy of fragments which have the source velocity v_3 and α is taken equal to 1 or $\frac{1}{2}$; the difference between the two values of α can be only checked if measurements at very forward angles are performed. This parametrization has been successfully used at high incident energies to describe emission from fireball /3,33/. In this model a piece of very hot nuclear matter with intermediate velocity is formed by the overlap between the projectile and the target. The fireball, in its reference frame, is assumed to deexcite through a volume Maxwellian type emission ($\alpha = \frac{1}{2}$) /34/ without Coulomb barrier

$$\frac{d^2\sigma}{d\Omega dE} \propto E^{\frac{1}{2}} \exp\left(-\frac{E}{T}\right)$$

which indicates that fragments are not emitted from a nucleus. Then the Coulomb repulsion from a stationary target spectator is approximated by replacing E by $E-ZC_3$ after transformation from the fireball frame to the laboratory system.

This parametrization was also used to reproduce precompound emission of light particles in our energy domain /35/ and more generally such a form without Coulomb repulsion is derived to reproduce energy distributions of evaporation residues and PLF in the Goldhaber approach /36/, then parameters T_3 depend on variances.

As a consequence the parametrization of the IVS must be regarded with caution to derive precise mechanism.

III.1 - What can be learned from the source parameters?

I shall focus the discussion on parameters T_3 and v_3 for which many data are available. If we make the assumption that the emitting source has reached thermodynamical equilibrium, T_3 is a true temperature. However we do not have any precise information showing that this assumption is correct. Moreover tests of the existence of such thermolyzed sources made by comparing T_3 to temperatures obtained by observing the relative population of two states for LF show that values disagree completely /37,38/. In these experiments the simplest picture of a system in thermal equilibrium with no feeding by particle decay was used to derive the temperature from the ratio R of the populations of two states:

$$R = \frac{(2 J_H + 1)}{(2 J_L + 1)} \exp\left(-\frac{\Delta E}{T}\right)$$

where J_L and J_H are the spins of the lower and higher states, respectively, and ΔE is the energy difference between the two states. In figure 4 results obtained for ^5Li and ^8Be are presented. The deduced values of T, around 5 MeV have to be compared with $T_3 \approx 20$ MeV. Therefore, T_3, that I shall call an apparent temperature, should simply be seen as a parameter representing the random momentum of LF. If we consider a fast multifragmentation process, the fragment keeps the momentum it had at the moment of breaking off and is left with an isotropic momentum distribution whose variance is given, following Goldhaber /36,39/, by:

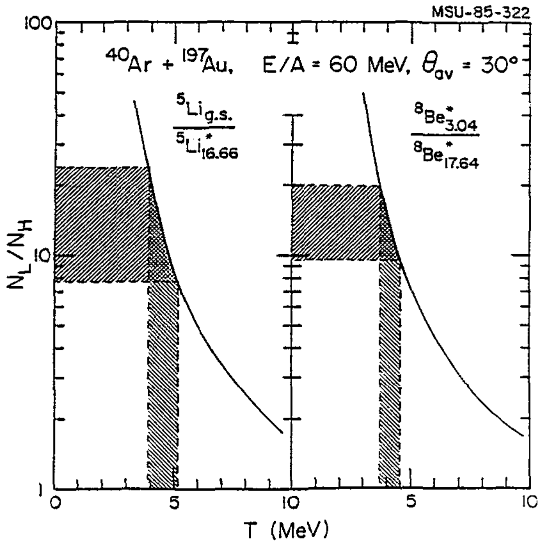

Fig. 4 - Yield ratios N_L/N_H (low over high) corresponding to the decays of ^{5}Li and ^{8}Be nuclei. The solid curves show the calculated ratios as a function of the temperature and the hatched regions indicate the range of experimental values. From /38/.

$$\sigma^2 = \frac{k_F^{\ 2}}{5} \cdot A_{LF} \cdot \frac{A_T - A_{LF}}{A_T - 1}$$

and $T_3 = \frac{\sigma^2}{A_{LF}}$

where A_T, A_{LF} are target and fragment mass and k_F denotes the Fermi momentum. In that case one expects an increase of T_3 with decreasing fragment mass. Such a behavior is generally observed experimentally and figure 5 shows an example. In addition one can also expect an

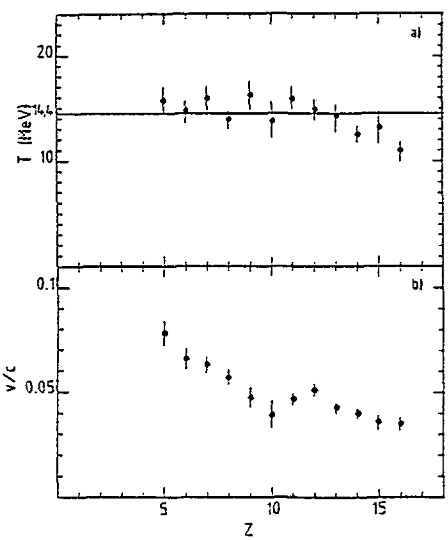

Fig. 5 - Temperatures (a) and source velocities (b) of the IVS for different Z in the reaction Ne + Au at 38 MeV/u. From /7/.

energy dependence of this apparent temperature, due to energy deposits and eventual compressed matter, and a more general form

$$T_3(E) = g(E) + \frac{\sigma^2}{A}$$

would be more realistic. In figure 6, apparent temperatures, averaged over several LF mass or Z, deduced from many experiments are reported as a function of the maximum excitation energy which can be deposited into the system (E^*/A); this quantity has been found very useful to compare data over a large range of incident energies and projectile-target pairs without any a priori concerning the involved mechanism.

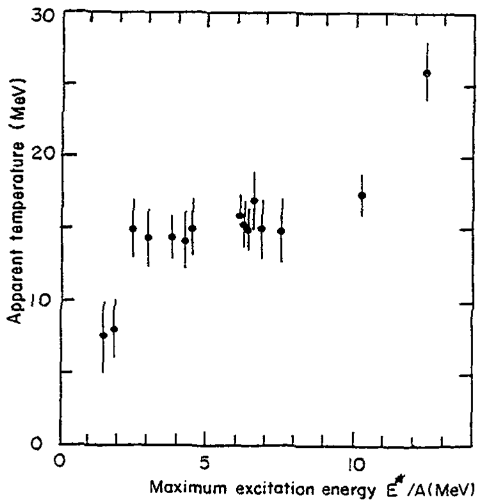

Fig. 6 - Average apparent temperatures of the IVS as a function of the maximum excitation energy per nucleon which can be deposited into the system E^*/A. Data are from /6,7,26,31,32,40,41/.

A very astonishing plateau is observed for E^*/A in the range 3-10 MeV and it is very tempting to compare this result with predictions of Bondorf et al. (figure 7) concerning multifragmentation /42/; however, the velocities found for IVS do not allow such E^*/A values to be attributed to the whole system.

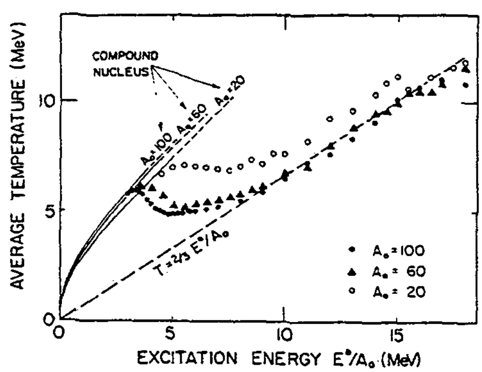

Fig. 7 - Average temperature of the "compound nucleus" as a function of the excitation energy the nucleon for different masses. At the crack $E^*/A \simeq 3$ MeV the temperature of the "compound nucleus" decreases or stays constant and the multifragmentation process sets in. From /42/.

Looking now at the values of v_3 one observes an increase with decreasing fragment mass (figure 5), as for T_3. The similar evolution of these two quantities shows again that the IVS cannot be seen as a hot zone in statistical equilibrium. Let us survey now the dependence of average values of v_3 on the mass asymmetry of the entrance channel. A strong correlation appears between v_3, normalized relatively to the projectile velocity, and a ratio specifying the relative sizes of the two nuclei (figure 8). It seems to be a clear indication that geometrical considerations (overlapping regions between projectile and target) play a role in the formation of the IVS or that most of these fragments could be emitted from an overlap region at a first step of the collision.

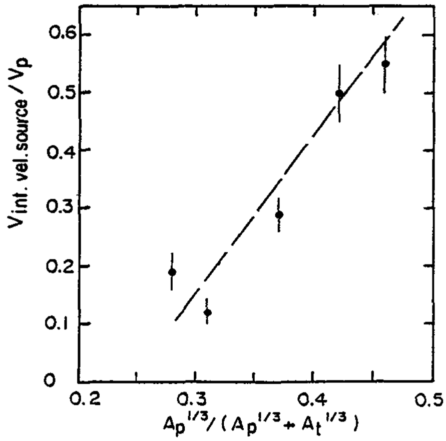

Fig. 8 - Evolution of average velocities of the IVS as a function of the geometrical parameter $A_p^{1/3}/(A_p^{1/3} + A_t^{1/3})$. Data were selected within a narrow maximum excitation energy range $4.45 < E^*/A < 6.85$. Data are from /6,7,31,32/

III.2 - Cross-sections: projectile, target and energy dependences

No reverse kinematic experiments studying the IVS cross-sections have been performed, it is why I shall speak of projectile and target dependence.

Figure 9 shows the most striking characteristic of the IVS: a strong increase of cross-sections with projectile mass. The factor 25 which is observed between carbon and argon indicates the very important role played by the size of the projectile (or smaller nucleus) for producing LF. On the contrary, a factor 2 on target mass does not have any

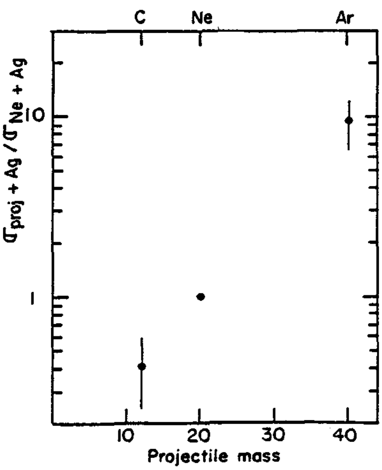

Fig. 9 - Projectile dependence of LF cross-sections from IVS. $6.20 < E^*/A < 7.53$. Data are from /5,6 32,43/.

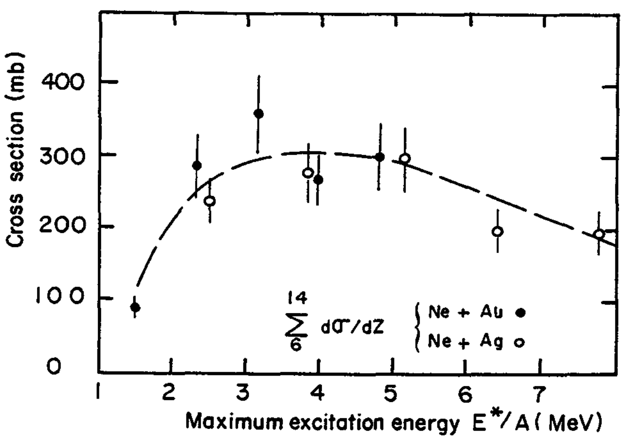

Fig. 10 - Evolution of LF cross-sections from IVS. The dashed line is just to guide the eye. Data are from /43/.

sizable effect (figure 10). This last observation is not in favour of a mechanism involving the whole system or essentially the target.

The evolution of cross-sections with incident energy or maximum excitation energy available for the system shows that values around 200-300 mb are observed for E^*/A larger than about 2 MeV. Such a rather constant value is very surprising if we believe that multifragmentation progressively takes over fusion-like process. But these results concern LF with Z larger than 5 and lower than 15 to avoid any contamination from eventual fission fragments. Finally, as suggested by the dashed line, cross-sections may slightly decrease towards high energy; such a fact observed for a given Z range cross-section indicates an enhancement of smaller LF at larger excitation energies (see fig. 12).

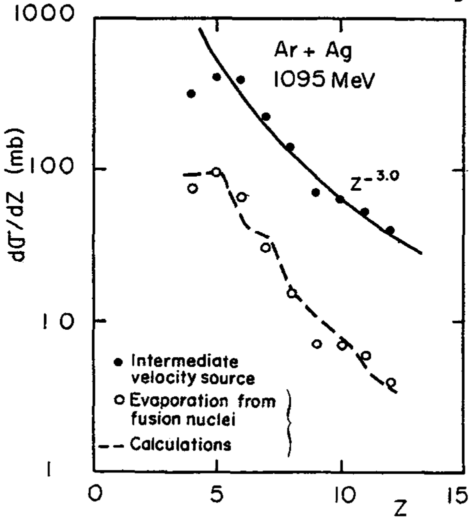

Fig. 11 - Experimental cross-sections for LF. Full points concern the IVS and solid line denotes $P(Z) \propto Z^{-3.0}$. PLF cross-sections are not indicated. From /47/.

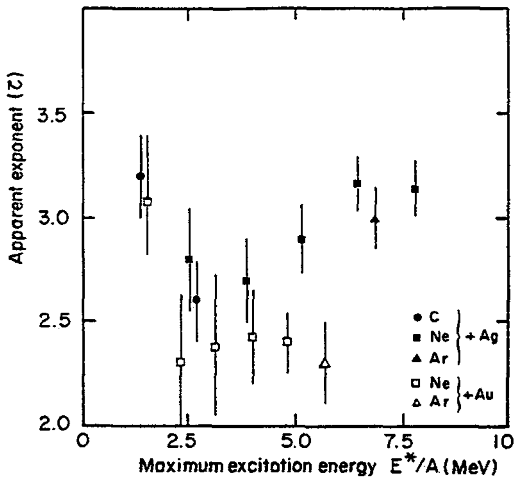

Fig. 12 - Apparent exponent of the power law as a function of the maximum energy per nucleon which can be deposited into the system E^*/A. Data are from /5,6,7,43/.

III.3 - The power law

The large interest inclined to a power law concerning LF mass or Z distributions comes from eventual cluster formation near the critical point. The nucleon-nucleon interaction is constituted by two components, a very short range repulsive one which takes account for compressibility of the medium and a short range attractive one which characterizes the strong interaction. Such a behavior allows to deduce properties of nuclear matter similar to those of Van der Waals liquids. Thus at and below the critical temperature, T_c, the cluster distribution has the form /22/

$$P(A) \propto A^{-K} \exp(-\, b(T)\, A^{2/3}) \simeq A^{-\tau(T)}$$

where b(T), the surface energy of the cluster divided by T, decreases monotically towards zero as $T \to T_c$ and K is found equal to 7/3 in mean field theory. As the temperature increases above T_c, the probability of finding heavy clusters falls off again and consequently the smallest value of the apparent exponent τ versus T reveals the critical temperature. However dynamical considerations and fluctuations around T_c /44/ probably hinder the system to reach the critical point with conditions requested for condensation. Moreover, it is necessary to underline that any model based on the minimum information principle (conservation laws and maximum entropy) will give mass or Z distributions following rather well a power law /45,46/.

Experimentally a power law is generally observed for LF distributions from IVS (fig. 11) and consequently it is very tempting to look at the evolution of the apparent exponent τ with temperature. But as it was seen previously, the values of T_3 derived from IVS parametrizations cannot be considered as "true temperatures", so figure 12 shows the evolution of the apparent exponent with E^*/A. Firstly, for E^*/A above 2.5 MeV, one observes a small influence of the target on the size of LF (or τ). Secondly a U shape seems to be observed with silver target, for which large E^*/A values were investigated, and a minimum around 3 MeV would be extracted. Unfortunately the lack of knowledge on the relation between the quantity E^*/A and the excitation energy of the emitting source prevents the deduction of any signification of this minimum.

IV - SUMMARY AND CONCLUSIONS

To summarize I will say that a few features come out from these inclusive measurements relative to the "unknown source" of LF.

i) It seems very difficult to attribute the LF production to evaporation from a hot zone in statistical equilibrium.

ii) Geometrical considerations deduced from velocities of the source and the crucial role, on cross-sections, of the projectile argue in favour of a mechanism in which the whole projectile participates.

iii) The weak role of the target mass suggests that only a part of it participates.

iv) The constant value of the apparent temperature of the source over a large energy range could be the signature of a multifragmentation process.

A mechanism in agreement with these features has been proposed two years ago /6,47/ in which a participant ball formed by the projectile spectator and the participant zone was the source emitting LF. A massive transfer from the target to the projectile could also be a possible way to form such a participant ball which then undergoes multifragmentation. However it is rather difficult to understand how in some cases, about 100 nucleons have to be transferred. Very recently exclusive measurements performed in Kr + Au reactions at 44 MeV/u have clearly shown the existence of an IVS /48/ emitting at least two fragments with Z larger than 7, which could be explained by the two mechanisms just mentioned. Finally I should stress that we cannot completely neglect the possibility of a pre-equilibrium emission.

I have tried to present an overview of what we know experimentally concerning LF emission from IVS. As usual these first experiments ask questions and it is quite clear that very exclusive measurements are strongly needed in order to enlighten this very exciting problem.

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